

EOS Validation Investigation Progress Report

10 June 1999

Title: A Study of Uncertainties for MODIS Cloud Retrievals of Optical Thickness and Effective Radius

Grant no: NAG5-6996

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Co-P.I.: Robert Pincus, University of Wisconsin, Madison

Funding Summary:

This proposal is being funded directly by the MODIS science team through the validation program in the EOS project science office. The grant was set up at UMBC in March 1998 for both investigators. As of September 1998, grant money for the portion of the investigation performed by R. Pincus (study of horizontal inhomogeneity effects) is sent directly to the University of Wisconsin. S. Platnick remains P.I. for the overall investigation.

Synopsis of Investigation:

Use model calculations, along with analysis of MODIS and MODIS Airborne Simulator (MAS) data, to assess the accuracy of the MODIS Cloud Product retrievals of liquid water cloud optical thickness and effective radius. Investigation to include, in no particular order:

- (1) Assessment of library errors: assess errors in the computation of reflectance and emission libraries used in the retrieval algorithm. Include such factors as wavelength integration, cloud droplet size distribution assumptions, complex index of refraction of water, etc.
- (2) Effect of instrument uncertainty and atmospheric corrections: examine the uncertainty produced by imperfect knowledge of the retrieval environment, including instrument performance and above-cloud atmospheric effects.
- (3) Effect of vertical inhomogeneity: investigate effects of vertical stratification in droplet size on retrieved optical properties, especially discrepancies between retrieved effective radii made from reflection measurements in different near-IR bands.
- (4) Effect of horizontal inhomogeneity: determine the uncertainties and biases due to horizontal inhomogeneity in cloud optical properties, and develop a theoretical framework for using image spatial variability to estimate pixel level uncertainty. Results will provide quantitative guidance for the assessment of quality assurance parameters for the MODIS cloud retrieval algorithm.

Scientific Progress and Results:

The MODIS cloud retrieval algorithm provides effective plane-parallel values of optical thickness and effective radius that give rise to the measured spectral reflectances. The physical meaning or use of these retrievals therefore depends on the degree to which real clouds are plane-parallel-like. As such, the past year's investigation concentrated on cloud inhomogeneity issues. Specifically, with regard to items (3) and (4) above:

(3) Effect of vertical inhomogeneity:

S. Platnick has finished developing a theoretical framework for assessing the influence of a vertical cloud droplet size profile on the three separate size retrievals available from the MODIS shortwave infrared bands (droplet size is inferred separately from each of the 1.6, 2.1, and 3.7 μm bands, in conjunction with a non-absorbing water band such as the 0.86 μm band). Completed work has included:

- (a) Modeled radiative and retrieval studies. *Results:* Several analytical models have been developed for use in the calculations, including single layer adiabatic parcel models and various non-adiabatic models. Forward calculations over a range of optical thicknesses and droplet sizes indicate that differences in the 1.6 and 2.1 μm size retrievals are expected to be nominal ($< 1 \mu\text{m}$) for adiabatic and sub-adiabatic aloft single layer clouds. However, 3.7 μm retrievals may often be significantly larger than the shorter wavelength retrievals ($> 1 \mu\text{m}$) and so statistically significant differences observed during operational retrievals are likely to be common. Extension to multilayer clouds depends on the details of the net vertical size profile.
- (b) Development of weighting functions for describing the information contributed by individual layers to the overall cloud droplet size retrieval. *Results:* A simple weighting, defined by the vertical distribution of maximum photon penetration, was found to predict retrieved sizes to generally within a tenth of a micron. Figure 1 shows examples of this weighting function for a visible and three shortwave infrared bands on MODIS.
- (c) Use of the weighting functions in an inversion of the size profile with the three separate shortwave infrared band retrievals. *Results:* given a minimal amount of measurement error, the three pieces of information are reduced to two pieces, not sufficient for inverting for a non-linear profile. A possible exception is when multiple viewing angles are available.

Results are being prepared for publication.

(4) Effect of horizontal inhomogeneity:

Stochastic cloud models:

There are several ways in which clouds can differ from the plane-parallel ideal, e.g., changes in cloud top height, changes in extinction (optical thickness), changes in both, to name a few. The impact of cloud top structure on retrievals is being assessed with a stochastic cloud model developed by R. Pincus. Reflected radiation in the MODIS retrieval bands is calculated for the modeled cloud fields with a three-dimensional radiative transfer code. Results are compared with plane-parallel models or input to a retrieval code. Initial results indicate that three dimensional effects in unbroken clouds are about the same size as other retrieval uncertainties.

(a) The model:

Realistic “bumpy” cloud top models are derived from four days of lidar data obtained over Atlantic stratocumulus cloud during the ASTEX field experiment in June 1994 (J. Spinhirne). The lidar measurements resolve cloud top height at 7.5 m in the vertical and 200 m in the horizontal. Two general measures of cloud variability that are used in developing a cloud model statistically equivalent to the measurements are spatial structure and height standard deviation (which is a function of scale). Several means for analyzing the height spatial structure (e.g., structure function analysis, spectral analysis) show that cloud top heights have an scale-invariant behavior from 200 m to about 12.8 km. For example, spatial analysis of the data shows that the second order structure function (one measure of spatial correlation as a function of distance) goes as L^α over these scales, where L is the distance scale and α varies from 0.4 - 0.55 from day to day. In addition to this scaling exponent, the four days of lidar observations also provide about 400 observations of the standard deviation of cloud top height at the 12.8 km scale, shown in Fig. 2. Taken together, these two pieces of information, the scaling exponent and standard deviation, provide a means of simulating 3D cloud top height fields. For assessing uncertainties in MODIS retrievals, cloud top height fields are specified within a 1 km pixel. Though each cloud realization will contain a random component, the height probability distribution function and spatial correlation will match the lidar data. An example cloud field is shown in Fig. 3. As many of these cloud fields can be constructed as needed. While differing in the details, each will be statistically equivalent.

(b) Preliminary results:

An initial investigation into the effect of variable cloud top heights on the radiation field (at MODIS cloud retrieval bands) has been completed. Reflectances are calculated using the Spherical Harmonics Discrete Ordinates Method (F. Evans, University of Colorado) as a function of viewing and illumination geometry. Results

have been compared with plane-parallel clouds having the same pixel-mean optical depth (assumptions made in converting cloud top height to extinction and optical depth within the pixel have little effect). In most of the angular space, reflectance differences are less than 2%; only larger errors only occur at extreme geometries (i.e. forward scattering at low sun and viewing angles) where MODIS retrievals will not be made operationally. The shortwave calibration accuracy for MODIS is targeted at 2%, indicating that retrievals in plane-parallel clouds will not be biased by the presence of cloud top structure.

Estimates of horizontal transport:

S. Platnick has developed an approximation for the root-mean-square horizontal transport of reflected and transmitted photons through a cloud, for both conservative and non-conservative scattering. The approximation is based on random walk theory and is a function of the average number of photon scatterings. The average number of scatterings can be calculated fast and efficiently for any combination of cloud model and solar/viewing geometry using a derived superposition procedure. Results are used to gauge the horizontal scales over which the plane-parallel assumptions need be valid (see Fig. 4). Results have been submitted for publication.

Publications:

Peer-reviewed publications directly resulting from investigation funded activities include:

Pincus, R., S. A. McFarlane, S. A. Klein, 1999: Albedo bias and the horizontal variability of clouds in subtropical marine boundary layers: Observations from ships and satellites *J. Geophys. Res.*, **104**, 6183-6191.

Platnick, S.: A superposition technique for deriving photon scattering statistics in plane-parallel cloudy atmospheres. *JQSRT*, May 1999, submitted.

Platnick, S.: Approximations for horizontal transport in cloud remote sensing problems. *JQSRT*, May 1999, submitted.

Conference presentations related to the investigation:

Platnick, S., M. D. King, S. Tsay, G. T. Arnold, H. Gerber, P. V. Hobbs, A. Rangno, 1999: A technique for cloud retrievals over snow and ice surfaces: results from FIRE-ACE, *AMS 10th Conference on Atmospheric Radiation*, 28 June - 2 July, Madison WI.

Pincus, R., A. Marshak, S. Platnick, and M. Gunshor, 1999: "Assessing the importance of cloud top topography on remote sensing retrievals", *AGU Spring Meeting*, 1-4 June, Boston MA.

Platnick, S., 1999: "Photon Transport in Cloud Remote Sensing Problems", *JCET Workshop on Radiative Transfer in Inhomogeneous Cloudy Atmospheres*, 7 June, Baltimore MD.

Platnick, S., J. Li, M. D. King, S. Tsay, G. T. Arnold, M. Gray, P. V. Hobbs, A. Rangno, 1999: Cloud bidirectional reflectance measurements of arctic stratus during FIRE-ACE. *ALPS 99 Symposium*, January 18-22, Meribel, France.

Activities for following year:

A portion of the coming year's work (Platnick) will deal with assessment of reflectance and emittance library errors (item 1 in the above synopsis). Effect of instrument and atmospheric correction uncertainties will be studied subsequently (item 2). The code required for generation of the libraries is in place, and a formula for the desired sensitivity parameter has been derived. R. Pincus will continue with investigations of inhomogeneous cloud effects, including stochastic cloud models.

Interaction with the MODIS science team:

Both S. Platnick and R. Pincus have been working closely with various members of the MODIS atmosphere science team. The involvement includes participation in validation field activities, including FIRE-ACE and SAFARI 2000. S. Platnick is a validation affiliate and adjunct team member of the atmosphere team.

Validation Investigation Web Page:

None at this time.

Effect of AM-1 launch delay:

Impact on the coming year's work is minimal. Subsequent efforts to gauge the correctness of the uncertainty studies will require MODIS validation and field campaign participation.

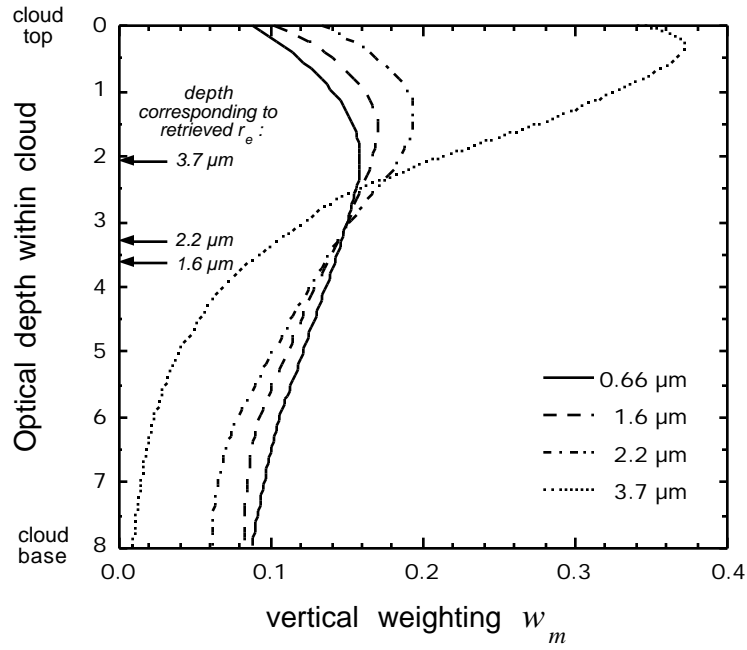


Fig. 1. Example normalized vertical weighting for selected visible and shortwave infrared MODIS bands. Calculated for a cloud with a total optical thickness of 8, effective radius varying from $5 \mu\text{m}$ at cloud base to $12 \mu\text{m}$ at cloud top with an assumed profile. The cloud optical depth corresponding to the retrieved radii for each of the three shortwave infrared bands is also indicated.

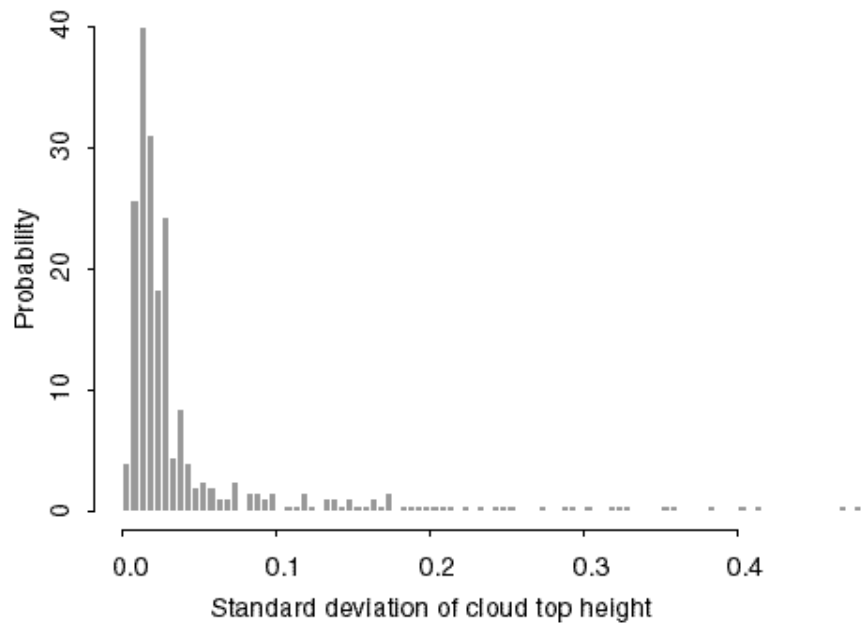


Fig. 2. Example of cloud top height standard deviation at a 12 km scale, for one day of lidar observations of stratocumulus marine clouds in the North Atlantic during ASTEX (June 1994).

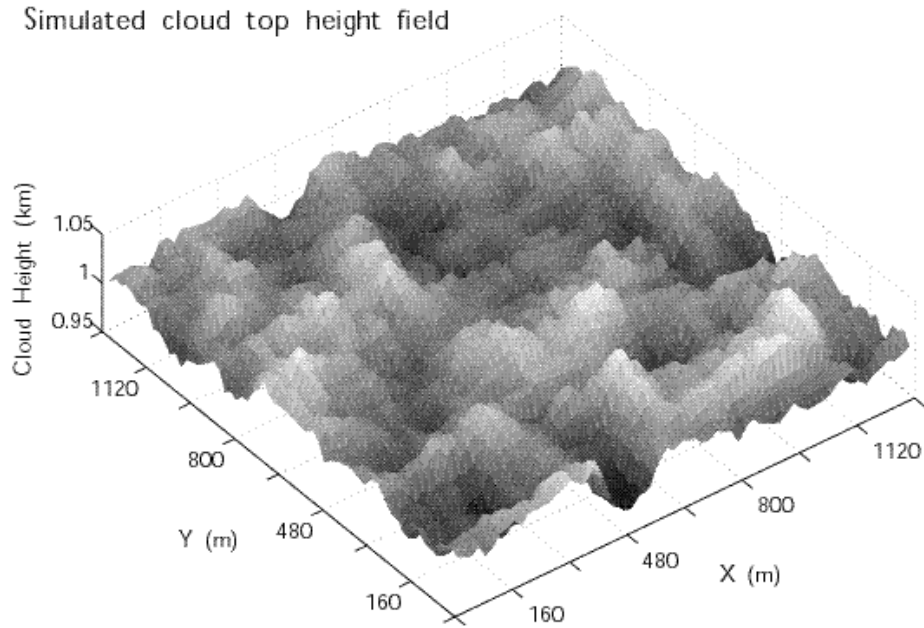


Fig. 3. Example of the 3-D stochastic cloud field. Cloud top heights are constructed to be statistically equivalent to the lidar observations.

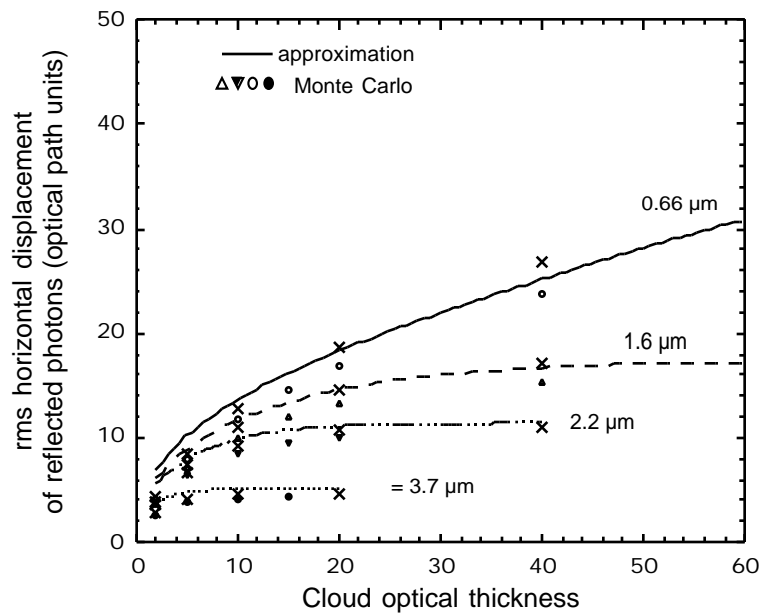


Fig. 4. Root-mean-square (*rms*) horizontal displacement for reflected photons as a function of cloud optical thickness in four MODIS spectral bands from 0.66 to 3.7 μm . Monte Carlo calculations (symbols) are compared with the approximate calculations (lines) for a homogeneous cloud with effective radius $r_e = 10 \mu\text{m}$.